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# Implication of the $D^0$ Width Difference On CP-Violation in $D^0$-$\bar{D}^0$ Mixing



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## Abstract

Both BaBar and Belle have found evidence for a non-zero width difference in the $D^0$-$\bar{D}^0$ system. Although there is no direct experimental evidence for CP-violation in $D$ mixing (yet), we show that the measured values of the width difference $y \sim \Delta\Gamma$ already imply constraints on the CP-odd phase in $D$ mixing, which, if significantly different from zero, would be an unambiguous signal of new physics.

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The highlight of this year's Moriond conference on electroweak interactions and unified theories arguably was the announcement by BaBar and Belle of experimental evidence for $D^0$-$\bar{D}^0$ mixing [1, 2, 3], which was quickly followed by a number of theoretical analyses [4, 5, 6, 7, 8, 9]. While Refs. [4, 7, 8, 9] focused on the constraints posed, by the experimental results, on various new-physics models, Ref. [5] presented a first analysis of the implications of these results for the fundamental parameters describing $D$ mixing. The purpose of this letter is to show that the present experimental results already imply constraints on a sizeable CP-odd phase in $D$ mixing, which could only be due to new physics (NP).

To start with, let us shortly review the theoretical formalism of $D$ mixing and the experimental results, see Refs. [10, 11] for more detailed reviews. In complete analogy to $B$ mixing, $D$ mixing in the SM is due to box diagrams with internal quarks and $W$ bosons. In contrast to $B$, though, the internal quarks are down-type. Also in contrast to $B$ mixing, the GIM mechanism is much more effective, as the contribution of the heaviest down-type quark, the $b$, comes with a relative enhancement factor $(m_b^2 - m_{s,d}^2)/(m_s^2 - m_d^2)$, but also a large CKM-suppression factor $|V_{ub}V_{cb}^*|^2/|V_{us}V_{cs}^*|^2 \sim \lambda^8$, which renders its contribution to $D$ mixing $\sim 1\%$ and hence negligible. As a consequence, $D$ mixing is very sensitive to the potential intervention of NP. On the other hand, it is also rather difficult to calculate the SM "background" to $D$ mixing, as the loop-diagrams are dominated by $s$ and $d$ quarks and hence sensitive to the intervention of resonances and non-perturbative QCD. The quasi-decoupling of the 3rd quark generation also implies that CP violation in $D$ mixing is extremely small in the SM, and hence any observation of CP violation will be an unambiguous signal of new physics, independently of hadronic uncertainties.

The theoretical parameters describing $D$ mixing can be defined in complete analogy to those for $B$ mixing: the time evolution of the $D^0$ system is described by the Schrödinger equation

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix} = \left(M - i\,\frac{\Gamma}{2}\right)\begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix} \tag{1}$$

with Hermitian matrices $M$ and $\Gamma$. The off-diagonal elements of these matrices, $M_{12}$ and $\Gamma_{12}$, describe, respectively, the dispersive and absorptive parts of $D$ mixing. The flavour-eigenstates $D^0 = (c\bar{u})$, $\bar{D}^0 = (u\bar{c})$ are related to the mass-eigenstates $D_{1,2}$ by

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle \tag{2}$$

with

$$\left(\frac{q}{p}\right)^2 = \frac{M_{12}^* - \frac{i}{2}\,\Gamma_{12}^*}{M_{12} - \frac{i}{2}\,\Gamma_{12}}\,; \tag{3}$$

$|p|^2 + |q|^2 = 1$ by definition.

The basic observables in $D$ mixing are the mass and lifetime difference of $D_{1,2}$, which are usually normalised to the average lifetime $\Gamma = (\Gamma_1 + \Gamma_2)/2$:

$$x \equiv \frac{\Delta M}{\Gamma} = \frac{M_2 - M_1}{\Gamma}\,, \quad y \equiv \frac{\Delta\Gamma}{2\Gamma} = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}\,. \tag{4}$$

In this letter we follow the sign convention of Ref. [5], according to which $x$ is positive by definition. The sign of $y$ then has to be determined from experiment. In addition, if there is CP-violation in the $D$ system, one also has

$$\left|\frac{q}{p}\right| \neq 1, \quad \phi \equiv \arg(M_{12}/\Gamma_{12}) \neq 0. \tag{5}$$

While previously only bounds on $x$ and $y$ were known, both BaBar and Belle have now found evidence for non-vanishing mixing in the $D$ system. BaBar has obtained this evidence from the measurement of the doubly Cabibbo-suppressed decay $D^0 \to K^+\pi^-$ (and its CP conjugate), yielding

$$\begin{aligned} y' &= (0.97 \pm 0.44(\text{stat}) \pm 0.31(\text{syst})) \times 10^{-2}, \\ x'^2 &= (-0.022 \pm 0.030(\text{stat}) \pm 0.021(\text{syst})) \times 10^{-2}, \end{aligned} \tag{6}$$

while Belle obtains

$$y_{\text{CP}} = (1.31 \pm 0.32(\text{stat}) \pm 0.25(\text{syst})) \times 10^{-2} \tag{7}$$

from $D^0 \to K^+K^-, \pi^+\pi^-$ and

$$x = (0.80 \pm 0.29(\text{stat}) \pm 0.17(\text{syst})) \times 10^{-2}, \quad y = (0.33 \pm 0.24(\text{stat}) \pm 0.15(\text{syst})) \times 10^{-2} \tag{8}$$

from a Dalitz-plot analysis of $D^0 \to K_S^0\pi^+\pi^-$. Here $y_{\text{CP}} \to y$ in the limit of no CP violation in $D$ mixing, while the primed quantities $x', y'$ are related to $x, y$ by a rotation by a strong phase $\delta_{K\pi}$:

$$y' = \cos\delta_{K\pi} - x\sin\delta_{K\pi}, \quad x' = x\cos\delta_{K\pi} + y\sin\delta_{K\pi}. \tag{9}$$

Limited experimental information on this phase has been obtainted at CLEO-c [12]:

$$\cos\delta_{K\pi} = 1.09 \pm 0.66\,, \tag{10}$$

which can be translated into $\delta_{K\pi} = (0 \pm 65)^\circ$. An analysis with a larger data-set is underway at CLEO-c, with an expected uncertainty of $\Delta\cos\delta_{K\pi} \approx 0.1$ in the next couple of years [13]; BES-III is expected to reach $\Delta\cos\delta_{K\pi} \approx 0.04$ after 4 years of running [14]. The experimental result (10) agrees with theoretical expectations, $\delta_{K\pi} = 0$ in the SU(3)-limit and $|\delta_{K\pi}| \lesssim 15^\circ$ from a calculation of the amplitudes in QCD factorisation [15]. Based on these experimental results, a preliminary HFAG-average was presented at the 2007 CERN workshop "Flavour in the Era of the LHC" [13]:

$$x = (8.5^{+3.2}_{-3.1}) \times 10^{-3}, \quad y = (7.1^{+2.0}_{-2.3}) \times 10^{-3}. \tag{11}$$

Adding errors in quadrature, this implies

$$\frac{x}{y} = 1.2 \pm 0.6. \tag{12}$$

The exact relations between $\Delta M$, $\Delta\Gamma$, $M_{12}$ and $\Gamma_{12}$ are given by

$$(\Delta M)^2 - \frac{1}{4}(\Delta\Gamma)^2 = 4|M_{12}|^2 - |\Gamma_{12}|^2,$$
$$(\Delta M)(\Delta\Gamma) = 4\mathrm{Re}(M_{12}^*\Gamma_{12}) = 4|M_{12}||\Gamma_{12}|\cos\phi\,. \tag{13}$$

Eq. (13) implies $x/y > 0$ for $|\phi| < \pi/2$ and $x/y < 0$ for $\pi/2 < |\phi| < 3\pi/2$. In view of the above experimental results, we assume $|\phi| < \pi/2$ from now on.

As for the CP-violating observables, $|q/p| \neq 1$ characterises CP-violation in mixing and can be measured for instance in flavour-specific decays $D^0 \to f$, where $\bar{D}^0 \to f$ is possible only via mixing. The prime example is semileptonic decays with

$$A_{\mathrm{SL}} = \frac{\Gamma(D^0 \to \ell^- X) - \Gamma(\bar{D}^0 \to \ell^+ X)}{\Gamma(D^0 \to \ell^- X) + \Gamma(\bar{D}^0 \to \ell^+ X)} = \frac{|q/p|^2 - |p/q|^2}{|q/p|^2 + |p/q|^2}\,. \tag{14}$$

Although the B factories may have some sensitivity to this asymmetry, its measurement is severely impaired by the fact that $D$ mixing proceeds only very slowly, resulting in a large suppression factor of the mixed vs. the unmixed rate:

$$\frac{\Gamma(D^0 \to \ell^- X)}{\Gamma(D^0 \to \ell^+ X)} = \frac{x^2 + y^2}{2 + x^2 + y^2} \approx 6 \times 10^{-5}. \tag{15}$$

Both in the $K$ and the $B$ system the quantity

$$A_M \equiv \left|\frac{q}{p}\right| - 1 \tag{16}$$

is very small, which however need not necessarily be the case for $D$'s. From (3) one derives the general expression

$$\left|\frac{q}{p}\right|^2 = \left(\frac{4 + r^2 + 4r\sin\phi}{4 + r^2 - 4r\sin\phi}\right)^{1/2} \tag{17}$$

with $r = |\Gamma_{12}/M_{12}|$ and the weak phase $\phi$ defined in (5). In the $B$ system, one has $r \ll 1$ (the current up-to-date numbers are $r \approx 7 \times 10^{-3}$ for $B_d$ and $r \approx 5 \times 10^{-3}$ for $B_s$ [16]), so that upon expansion in $r$

$$\left|\frac{q}{p}\right|^2_{B_{d,s}} = 1 + \left|\frac{\Gamma_{12}}{M_{12}}\right| \sin\phi + O(r^2). \tag{18}$$

Note that this formula refers to the definition $\phi = \arg(M_{12}/\Gamma_{12})$, which differs by $+\pi$ from the one used in Ref. [16], $\phi = \arg(-M_{12}/\Gamma_{12})$. For the $K$ system, one finds $r \approx |\Delta\Gamma/\Delta M| \approx 2$ from experiment, but now the phase $\phi$ turns out to be small, so that

$$\left|\frac{q}{p}\right|^2_K = 1 + \frac{4r}{4 + r^2}\,\phi + O(\phi^2) \approx 1 + \phi. \tag{19}$$

In both cases, $|q/p| \approx 1$ to a very good approximation. In the $D$ system, however, there is no natural hierarchy $r \ll 1$, and of course one hopes that NP-effects induce $|\phi| \gg 0$. In

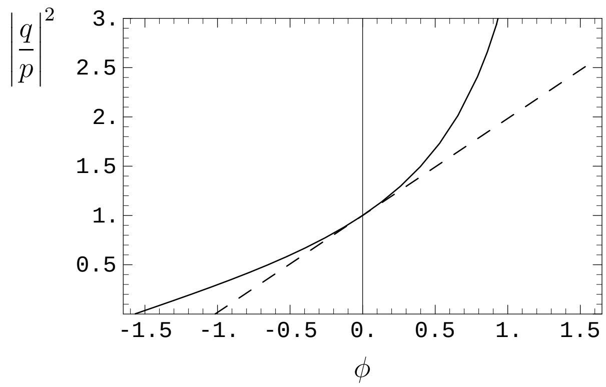


Figure 1: $|q/p|^2$, Eq. (20), as a function of the CP-odd phase $\phi$ for the central experimental value $\tilde{r} = 7.1/8.5$. Solid line: full expression, dashed line: first order expansion around $\phi = 0$.

this case, and because $x$ and $y$ have been measured, while $|M_{12}|$ and $|\Gamma_{12}|$ are difficult to calculate, it is convenient to express $|q/p|_D$ in terms of $x$, $y$, $\phi$, using the exact relations (13). From (3), and defining $\tilde{r} = y/x$, we then obtain

$$\left|\frac{q}{p}\right|^2 = \frac{1}{\sqrt{2}(1+\tilde{r}^2)} \left\{ 2(1+\tilde{r}^2)^2 + 16\tilde{r}^2 \tan^2\phi \right.$$
$$\left. +8\tilde{r}\tan\phi\sec\phi\sqrt{(1+\tilde{r}^2)^2 - (1-\tilde{r}^2)^2\sin^2\phi} \right\}^{1/2}. \tag{20}$$

Note that for finite $xy$ and $\phi = \pm\pi/2$, $|q/p|$ diverges because $xy \to 0$ for $\phi \to \pm\pi/2$ from (13). In Fig. 1 we plot $|q/p|^2$ as function of $\phi$, for the central experimental value from HFAG, $\tilde{r} = 7.1/8.5$, Eq. (11). It is obvious that even for moderate values of $\phi$ the small-$\phi$ expansion is not really reliable.

What is the currently available experimental information on CP-violating in $D$ mixing, i.e. $|q/p|$ and $\phi$? As already mentioned, the semileptonic CP-asymmetry (14) has not been measured yet. What has been measured, though, is the effect of CP-violation on the time-dependent rates of $D^0 \to K^+\pi^-$ and $\bar{D}^0 \to K^-\pi^+$. The BaBar collaboration has parametrised these rates as

$$\Gamma(D^0(t) \to K^+\pi^-) \propto e^{-\Gamma t}\left[R_D + \sqrt{R_D}y'_+\Gamma t + \frac{x'^2_+ + y'^2_+}{4}(\Gamma t)^2\right],$$
$$\Gamma(\bar{D}^0(t) \to K^-\pi^+) \propto e^{-\Gamma t}\left[R_D + \sqrt{R_D}y'_-\Gamma t + \frac{x'^2_- + y'^2_-}{4}(\Gamma t)^2\right] \tag{21}$$

and fit the $D^0$ and $\bar{D}^0$ samples separately. They find [2]

$$y'_+ = (9.8 \pm 6.4(\text{stat}) \pm 4.5(\text{syst})) \times 10^{-3},$$
$$y'_- = (9.6 \pm 6.1(\text{stat}) \pm 4.3(\text{syst})) \times 10^{-3}. \tag{22}$$

Adding errors in quadrature, this means $y'_+/y'_- = 1.0 \pm 1.1$. BaBar also obtains values for $x'^2_\pm$ which we do not quote here, because the sensitivity to the quadratic term in (21) is

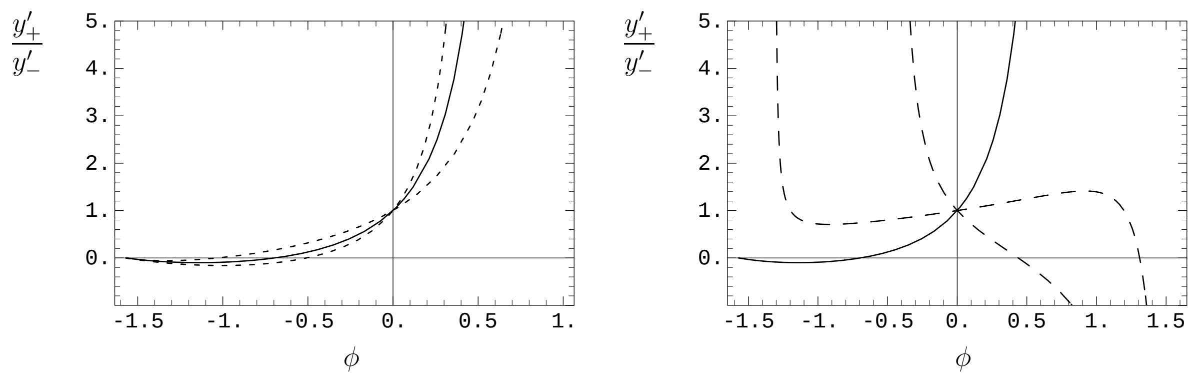


Figure 2: Left: $y'_+/y'_-$ as function of $\phi$ for $x/y = 1.2$ (solid line) and $x/y = \{0.6, 1.8\}$ (dashed lines), from Eq. (11). $\delta_{K\pi} = 0$. Right: $y'_+/y'_-$ as function of $\phi$ for $x/y = 1.2$ for $\delta_{K\pi} = 0$ (solid line) and $\delta_{K\pi} = \pm 65°$ (dashed lines).

less than that to the linear term in $y'_\pm$. $R_D^{1/2}$ is the ratio of the doubly Cabbibo-suppressed to the Cabibbo-favoured amplitude, $R_D^{1/2} = |A(D^0 \to K^+\pi^-)/A(D^0 \to K^-\pi^+)|$. $\delta_{K\pi}$ is the relative strong phase in the Cabibbo-favoured and suppressed amplitudes:

$$\frac{A(D^0 \to K^+\pi^-)}{A(\bar{D}^0 \to K^+\pi^-)} = -\sqrt{R_D} e^{-i\delta_{K\pi}}; \tag{23}$$

the minus-sign comes from the relative sign between the CKM matrix elements $V_{cd}$ and $V_{us}$. In the limit of no CP-violation in the decay amplitude, one has $|A(D^0 \to K^-\pi^+)| = |A(\bar{D}^0 \to K^+\pi^-)|$, which is expected to be a very good approximation, in view of the fact that the decay is solely due to a tree-level amplitude. Then the relation of $y'_\pm$ to $x$, $y$ and $\phi$ is given by

$$\begin{aligned} y'_+ &= \left|\frac{q}{p}\right| \{(y\cos\delta_{K\pi} - x\sin\delta_{K\pi})\cos\phi + (x\cos\delta_{K\pi} + y\sin\delta_{K\pi})\sin\phi\}, \\ y'_- &= \left|\frac{p}{q}\right| \{(y\cos\delta_{K\pi} - x\sin\delta_{K\pi})\cos\phi - (x\cos\delta_{K\pi} + y\sin\delta_{K\pi})\sin\phi\}. \end{aligned} \tag{24}$$

Presently, the experimental result for $y'_+/y'_-$ is compatible with 1, although with considerable uncertainties. Any significant deviation from 1 would be a sign for new physics. In Fig. 2 we plot $y'_+/y'_-$ as function of $\phi$, for different values of $x/y$ and $\delta_{K\pi}$. The figures clearly show that the value of $y'_+/y'_-$ is very sensitive to the phase $\phi$, at least if $\delta_{K\pi}$ is not too close to $-65°$, which corresponds to the nearly constant dashed line in Fig. 2b. The reason for this dependence on $\delta_{K\pi}$ becomes clearer if $y'_+/y'_-$ is expanded to first order in $\phi$:

$$\frac{y'_+}{y_-} = 1 - 2\phi\, \frac{x(x^2+2y^2)\cos\delta_{K\pi} + y^3\sin\delta_{K\pi}}{(x^2+y^2)(x\sin\delta_{K\pi} - y\cos\delta_{K\pi})} + O(\phi^2). \tag{25}$$

For the central values of $x$ and $y$, Eq. (11), this amounts to $1 + 3.4\phi$ for $\delta_{K\pi} = 0$, $1 - 3.3\phi$ for $\delta_{K\pi} = +65°$ and $1 + 0.45\phi$ for $\delta_{K\pi} = -65°$, which explains the shape of the curves in Fig. 2b. Evidently it is important to reduce the uncertainty of $\delta_{K\pi}$, which, as mentioned

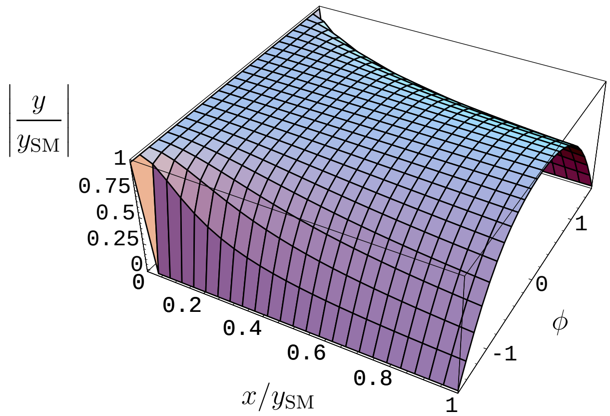


Figure 3: Plot of $|\Delta\Gamma/\Delta\Gamma^{\rm SM}|$, Eq. (26), as a function of $x/y_{\rm SM}$ and $\phi$.

earlier, will be achieved within the next few years. On the other hand, as shown in Fig. 2a, $y'_+/y'_-$, which depends only on the ratio $x/y$, but not $x$ and $y$ separately, is not very sensitive to the precise value of that ratio, but very much so to $\phi$. The conclusion is that, even if $x/y$ itself cannot be determined very precisely, $y'_+/y'_-$ will nonetheless be a powerful tool to constrain $\phi$, at least once $\delta_{K\pi}$ will be known more precisely. Already now very large values $\phi \sim \pi/2$ are excluded.

Another, more theory-dependent constraint on $\phi$ can be derived from the value of $y$. This argument centers around the fact that (a) the experimental result (11) is at the top end of theoretical predictions $y_{\rm SM} \sim 1\%$ [17] and (b) new physics indicated by a non-zero value of $\phi$ always *reduces* the lifetime difference, independently of the value of $x$. This observation is similar to what was found, some time ago, for the $B_s$ system [18]. In order to derive it, we assume that new physics does not affect $\Gamma_{12}$,[1] so that $\Gamma_{12} = \Gamma_{12}^{\rm SM}$. We then have $2|\Gamma_{12}| = \Delta\Gamma^{\rm SM}$ and hence $|y_{\rm SM}| = |\Gamma_{12}|/\Gamma$. Using the relations (13), we can then express the ratio $|\Delta\Gamma/\Delta\Gamma^{\rm SM}|$ in terms of $y_{\rm SM}$, $x$ and $\phi$:

$$\left|\frac{y}{y_{\rm SM}}\right| = \left|\frac{\Delta\Gamma}{\Delta\Gamma^{\rm SM}}\right| = \left(\frac{y_{\rm SM}^2 + x^2}{y_{\rm SM}^2 + x^2/\cos^2\phi}\right)^{1/2}. \tag{26}$$

This implies that *new physics always reduces the lifetime difference*, independently of the value of $x$ (and any new physics in the mass difference). In particular one has $y = 0$ for $\phi = \pm\pi/2$ and $x \neq 0$, which follows from the 2nd relation (13). Eq. (26) is the manifestation of the fact that one does not need to observe CP-violation in order to constrain it. A famous example for this is the unitarity triangle in $B$ physics, whose sides are determined from CP-conserving quantities only, but nonetheless allow a precise measurement of the size of CP-violation in the SM, via the angles and the area of the triangle. In Fig. 3, we plot $|\Delta\Gamma/\Delta\Gamma^{\rm SM}|$ as a function of $r = x/y_{\rm SM}$. The zero at $\phi = \pm\pi/2$ is clearly visible. The experimental value $|y/y_{\rm SM}| = O(1)$ then excludes phases $\phi$ close to $\pm\pi/2$. In order to make more quantitative statements, apparently a more precise calculation of $y_{\rm SM}$ is needed.

[1] See, however, Ref. [19] for a discussion of the effect of tiny NP admixtures to $\Gamma_{12}$.

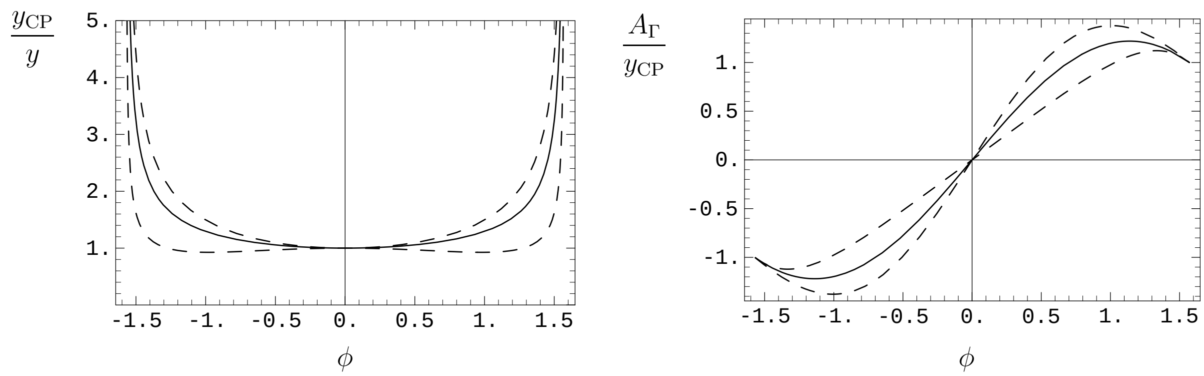


Figure 4: Left: $y_{\rm CP}/y$ as function of $\phi$, for $x/y = 1.2$ (solid line) and $x/y = \{0.6, 1.8\}$ (dashed lines), see Eq. (12). Right: $A_\Gamma/y_{\rm CP}$ as function of $\phi$.

Two more CP-sensitive observables related to $D^0 \to K^+K^-$ have been measured by the Belle collaboration [3]:

$$\begin{aligned} y_{\rm CP} &= \frac{1}{2\Gamma}\left[\Gamma(D^0 \to K^+K^-) + \Gamma(\bar{D}^0 \to K^+K^-)\right] - 1 \\ &= \frac{1}{2}\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) y\cos\phi + \frac{1}{2}\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) x\sin\phi, \end{aligned} \tag{27}$$

$$\begin{aligned} A_\Gamma &= \frac{1}{2\Gamma}\left[\Gamma(D^0 \to K^+K^-) - \Gamma(\bar{D}^0 \to K^+K^-)\right] - 1 \\ &= \frac{1}{2}\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) y\cos\phi + \frac{1}{2}\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) x\sin\phi. \end{aligned} \tag{28}$$

The present experimental value of $y_{\rm CP}$ is given in (7), that for $A_\Gamma$ is $(0.01 \pm 0.30(\text{stat}) \pm 0.15(\text{syst})) \times 10^{-2}$. Again, we can study the dependence of these observables on $\phi$. In Fig. 4a we plot the ratio $y_{\rm CP}/y$, which is a function of $x/y$ and $\phi$, in dependence on $\phi$. As it turns out, this quantity is far less sensitive to $\phi$ than $y'_+/y'_-$, the reason being that its deviation from 1 is only a second-order effect in $\phi$:

$$y_{\rm CP} = y\left\{1 + \phi^2\,\frac{x^4 + x^2y^2 - y^4}{2(x^2+y^2)^2} + O(\phi^4)\right\}. \tag{29}$$

Hence, unless the experimental accuracy is dramatically increased, and because the results on $y'_+/y'_-$ and $y/y_{\rm SM}$ already exclude a large CP-odd phase $\phi \approx \pm\pi/2$, it is safe to interpret $y_{\rm CP}$ as measurement of $y$. In Fig. 4b we plot the quantity $A_\Gamma/y_{\rm CP}$. Also here there is a distinctive dependence on $\phi$, with $A_\Gamma/y \propto \phi$ for small $\phi$, but the effect is less dramatic than that in $y'_+/y'_-$.

In conclusion, we find that the experimental results on $D$ mixing reported by BaBar and Belle already exclude extreme values of the CP-odd phase $\phi$ close to $\pm\pi/2$. This follows from the result for $y$, which is close to the top end of theoretical predictions and can only be *reduced* by new physics, and from $y'_+/y'_- \sim 1$. While $y'_+/y'_- - 1$ vanishes in the limit of no CP-violation, $y \sim \Delta\Gamma$ is a CP-conserving observable, which demonstrates

the usefulness of such quantities in constraining CP-odd phases. Also $y_{\rm CP}$, $A_\Gamma$ and the ratio $A_\Gamma/y_{\rm CP}$ can be useful in constraining $\phi$. As long as there is no major breakthrough in theoretical predictions for $D$ mixing, which are held back by the fact that the $D$ meson is at the same time too heavy and too light for current theoretical tools to get a proper grip on the problem, the long-distance SM contributions to $x$ will completely obscure any NP contributions and their detection. The observation of CP violation, however, presents a theoretically clean way for NP to manifest itself and it is to be hoped that in the near future, i.e. at the $B$ factories or the LHC, at least one of the plentiful opportunities for NP to show up in CP violation [20] will be realised.

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